FLEXIBLE FORMING OF THIN ALUMINUM ALLOY SHEETS

Fabrizio Quadrini [1], Loredana Santo [1] & Erica Anna Squeo [1]

[1] University of Rome "Tor Vergata", Department of Mechanical Engineering,
Via della Ricerca Scientifica, 062023867 Rome, Italy

Corresponding author: Fabrizio Quadrini, quadrini@ing.uniroma2.it

Abstract: Flexible forming is a sheet metal forming process with the application of soft material tooling. In this study, flexible (silicone rubber, SR, and styrene butadiene rubber, SBR) and semi-rigid (polyamide 66, PA) polymeric materials were adopted to make several upper dies which were used in combination with aluminium lower dies. Stamping operations were performed on a thin aluminium alloy sheet with two different geometries: a cylindrical cup and a straight rib. Small samples were produced and analysed by visual inspection and profilometry. Forming forces were measured during process so as to compare the effect of the different die materials on the process performances. Numerical analyses were also used for a better understanding of the forming procedure. Best results were obtained in the case of semi-rigid dies, whereas flexible dies led to sheet tearing, and generally exhibited poor durability.
Key words: Sheet metal, sheet forming, flexible forming, rubber forming, aluminium alloy.

1. INTRODUCTION

Sheet metal forming processes are widely used to produce complex parts, and consist of a series of basic operations, like bending, stretching, stamping and blanking. Among sheet metal forming, flexible forming is a new process for the production of sheet metal parts with complex shapes by using a flexible medium, such as rubber, as a die. Recently, rubber forming processes have gained interest since they have been used extensively in the aircraft industry. The advantages of flexible forming over conventional forming processes are principally low cost tooling, versatility of the process, and low damaging of the formed parts.

Rubber forming had its beginnings in the latter part of the 19th century (Thiruvarudchelvan, 1993). In 1993, in his review on elastomers in metal forming, Thiruvarudchelvan individuated several processes: the Guerin process (which used an enclosed rubber pad); the Marform process (with the addition of an independent blank-holder); the Verson- Wheelon process (which used a comparatively lighter press with an inflatable rubber bag); bending, roll forming; blanking and piercing; embossing; deep drawing; free forming; tube bulging. In this review, urethanes were considered the best materials for flexible tools because of their good oil and solvent resistance, good wear resistance, high thermal stability and load-bearing capacity. In 1995, Browne and Battikha studied the aluminium sheet forming (by Guerin process and Marform process) using a flexible die made of neoprene or commercial rubber (Browne and Battikha, 1995). They concluded that flexible forming is capable of producing, from thin aluminium alloy sheet, shallow formed parts with good surface finish and little metal thinning. Tooling costs are reduced considerably as only one form block needs to be manufactured per component. Also the time to production is low because of the system simplicity which enables the rapid production of prototype parts. In a last contribution, the application of prototyping techniques like stereolithography was discussed for the production of flexible tools in polyurethane (Müller and Sladojevic, 2001).

Despite of the big interest in this technology, scanty information are available in the scientific literature about flexible forming. Many important aspects have not been deepened yet such as the effect of the viscoelatic behaviour of the tool flexible material on the process performances, or the durability of the flexible tool. Moreover, even if new high performance materials have been introduced into the market in the last decade, their suitability for rubber forming has not been evaluated.

In this study, flexible forming of aluminium alloy thin sheets is studied. In particular, different die geometries and materials were used (namely silicone rubber, SR, styrene butadiene rubber, SBR, and polyamide 66, PA) to form simple shapes. SR and SBR can be considered flexible materials whereas PA has to be considered a semi-rigid material. During experimentation, the forming forces were evaluated together with the part spring-back, and a simple numerical procedure was implemented to predict the sheet behaviour under forming. In fact, numerical simulation is fundamental to investigate innovative sheet metal forming processes (Alberti and Fratini, 2004), and to reduce development time and cost in small series production (Sala, 2001). During the conceptual design of rubber forming operations, possible technological troubles are preliminarily faced by means of numerical analyses.

2. MATERIALS AND METHODS

2.1 The experimental apparatus

A universal material testing machine (Alliance RT/50 by MTS) was used to characterize base materials and to perform forming tests. A surface analyzer (Talysurf CLI 2000) was used to measure the sheet metal spring-back after forming.

2.2 The aluminium sheet

A thin aluminium alloy sheet (namely Al 1200) with a thickness of 150 µm was used for forming tests. Tensile tests were carried out on dog-bone shaped specimens cut from the metal sheet along two perpendicular directions. This way, the effect of the material orientation (due to rolling-calendering) on its performances was evaluated. The specimens were 150 mm long and 10 mm wide with a 65 mm gage-length; the test rate was 1 mm/min. The aspect of some specimens after testing is shown in Fig.1, whereas some tensile tests are reported in Fig.2: the longitudinal direction refers to the calendering one. Apart from data scattering, due to the specimen extraction, higher ductility and strength was measured along the longitudinal direction. In particular, yield strength of 125±3 MPa was measured along the longitudinal direction, and a value of 116±5 MPa along the transverse direction. It is reasonable that the sheet anisotropy could affect the further forming operation in terms of sheet tearing or distortions. Rubber forming, in the Guerin process, is performed by means of two matching dies: a flexible die (which is generally the upper die) and a rigid die (the lower die).

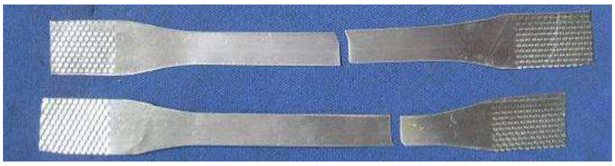

Fig. 1. Aspect of aluminium alloy specimens after tensile tests

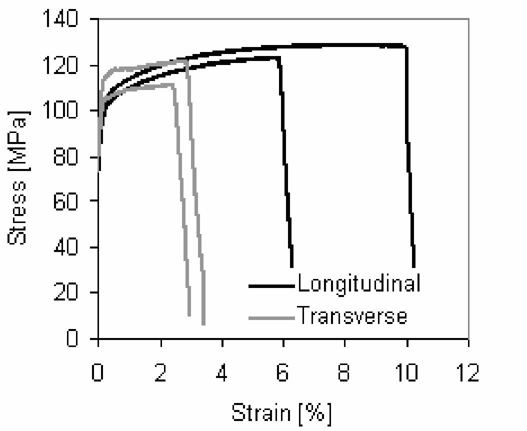

Fig. 2. Effect of the aluminium sheet direction on the tensile tests

2.3 The rigid dies

Three different rigid lower dies were used in the experimentation (Fig.3): a truncated conical cup, 4 mm deep, with a maximum diameter of 20 mm and a minimum diameter of 15 mm (therefore with a cone angle of 58 deg); a straight rib with a rectangular cross section, 2 mm deep, 40 mm long, and 10 mm wide; a second straight rib with the same rectangular shape but 6 mm deep. All the lower dies were made in aluminium alloy (6000 series).

2.4 The flexible dies

Three different materials were selected for the fabrication of the flexible dies: two very soft and flexible rubbers (SR and SBR) and a semi-rigid plastic (PA66). In order to show the difference in mechanical properties between SR and SBR, a compression test was carried out at 5 mm/min (Fig.4): it is evident that SR is softer than SBR at low strains but its rigidity increases suddenly near 50% of strain. It is expected that this remarkable difference in the mechanical behaviour could result in a strong difference of the SR and SBR dies during forming.

Both flat and shaped dies were manufactured in all the materials (apart from PA which was used only for shaped dies, because of the high stiffness). In the case of SR and SBR shaped die, the aluminium rigid dies (Fig.3) were used for shaping so as to guarantee the die matching. SR dies were fabricated starting from liquid silicone which was poured on the aluminium dies and left to harden.

SBR dies were fabricated by compression moulding of SBR rubber powder on the same aluminium dies. PA dies were manufactured by machining an extruded bar: both the upper and the lower dies were machined and a clearance about 200 µm was considered after matching.

Fig. 3. Rigid lower dies

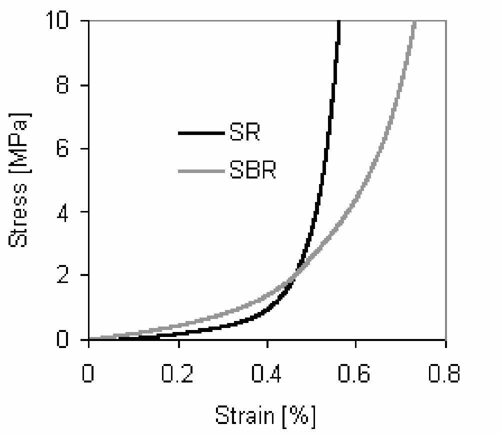

Fig. 4. Compression test of a SR and a SBR sample

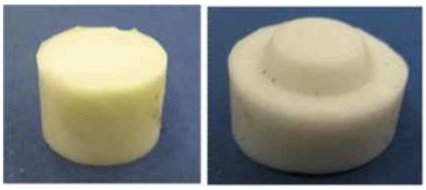

Fig. 5. SR dies: flat (left) and shaped (right) upper dies for forming conical cups

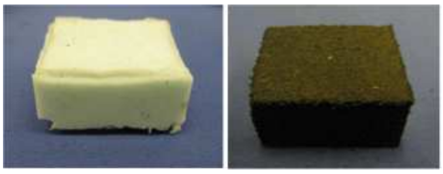

Fig. 6. An SR (left) and SBR (right) flat upper die for forming straight ribs

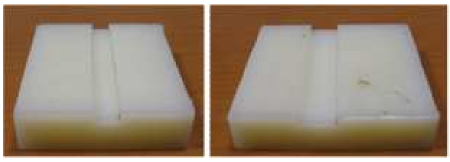

Fig. 7. PA lower dies for forming straight ribs: 6 mm (left) and 10 mm (right) width of the rib

Fig. 8. Upper dies for forming the 10 mm wide straight rib: SR (left), SBR (centre), and PA (right)

Figs. 4-6 show some flexible dies: SR dies for flexible forming of the cup (Fig.5); flat SR and SBR dies for straight ribs (Fig.6); PA lower dies for straight ribs (Fig.7); upper dies for the wider straight rib (Fig.8).

2.5 The forming process

Flexible forming was carried out by means of the Guerin process. In Fig.9 the adopted forming apparatus is described in the case of the straight rib: between the compression plates of the universal material testing machine, the upper and the lower dies were placed. For the softer materials (SR and SBR) a die holder was used so as to reduce material flow during pressing. For PA dies, it was not necessary to use a die holder thanks to their high stiffness: Fig.9 and 10 show the forming system for the straight rib, in the case of SR and PA dies respectively. The same forming configuration of Fig.9 was also used for the conical cup.
All the forming tests were carried out at 5 mm/min, apart some tests which are specifically mentioned in the following. Square (about 30x30 mm^2) aluminium sheets were used for straight ribs and circular ones (diameter of 25 mm) for conical cups.

3. EXPERIMENTAL RESULTS

3.1 SR dies

In Fig.11 the forming curves of conical cups, produced by means of flat SR dies, are shown.

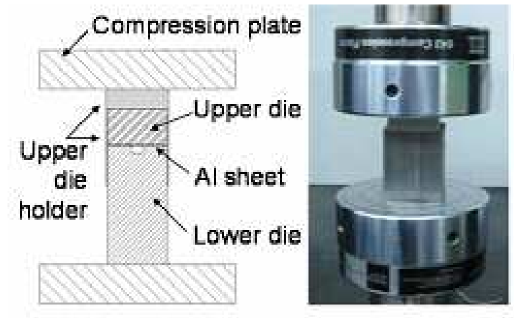

Fig. 9. Forming system for the straight rib

Fig. 10. Forming system with lower and upper PA dies

In this case, the effect of the forming rate was also evaluated by using three different velocities of the machine plate (5, 10 and 20 mm/min). By increasing the forming rate, lower displacements are necessary to form the sheet, because of the higher material rigidity. However, a good formability was never observed: the complete forming of the cup was never obtained. By increasing the displacement during forming, several defects compare: wrinkling of the plain sheet; tearing of the sheet near the lower die edge. The occurrence of tearing is clearly visible in the curves of Fig.11 by means of the relative peaks. By using lower displacements, the sheet formability was very poor. Negligible differences were observed by using shaped dies rather than flat dies.
Fig.12 shows the appearance of two formed cups. In order to reduce wrinkling, straight ribs were preferred in the following experimentation. Because of the strong dependence of the forming curves on the forming rate, it was expected that other parameters (such as the die height) could be important during the forming procedure.

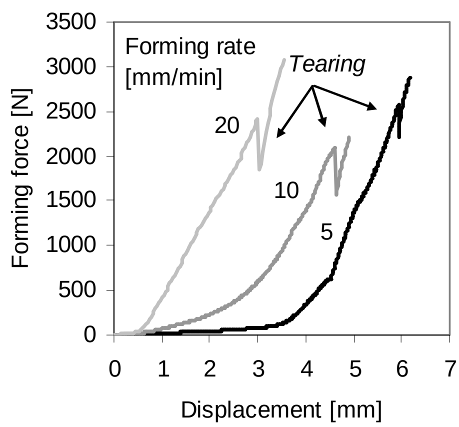

Fig. 11. Forming curves for conical cups with flat SR dies

Fig. 12. Defects of formed cups by SR dies

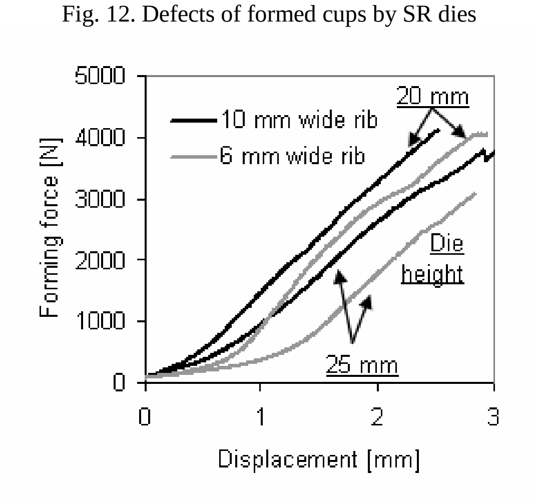

Fig. 13. Forming curves for straight ribs with flat SR dies

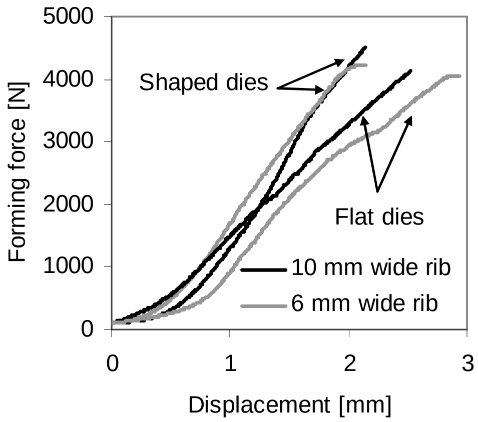

Fig. 14. Effect of die shape on forming curves for SR dies

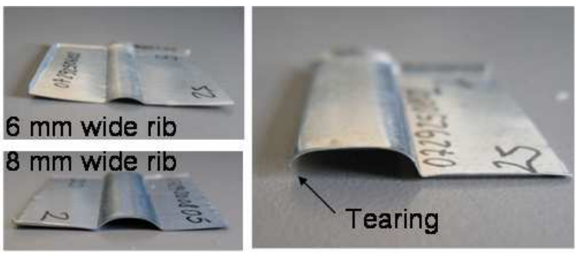

Fig. 15. Defects of formed straight ribs by SR dies

The effect of the die height on the forming curves is shown in Fig.13 in the case of straight ribs and flat SR dies. At fixed die height, higher forming curves were observed for wider ribs, probably due to the difference of friction forces between the aluminium die and the aluminium sheet. However, higher forming curves were not correlated with good sheet shaping. An opposite trend was observed at fixed rib width: by increasing the die height, lower forming curves were measured because of the reduction of the die stiffness.

Fig. 16. SR die damaging

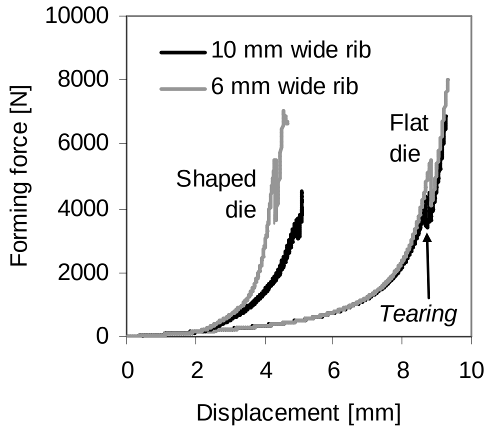

Fig. 17. Forming curves for straight ribs with flat and shaped SBR dies

The effect of the die shape is shown in Fig.14 where a comparison is provided between forming curves with flat dies and shaped dies. Higher forming curves were observed for shaped dies probably due to the local compression effect of the die protrusion. For the same effect, an opposite dependence of the forming curve on the rib width was observed in comparison with flat dies: by increasing the rib width, lower forming curves were obtained.

However, also for straight ribs, it was never observed a good matching of the aluminium sheet with the lower aluminium die, independently from the die shape. The SR dies were not able to produce a sufficient material flow during stamping, and sheet tearing easily occurred (Fig.15). However, the biggest problem was not related to the poor formability but to the very low durability of the dies: after few stamping operations the SR dies were seriously damaged due to the excess in the deformation (Fig.16).

3.2 SBR dies

SBR dies are stiffer than SR dies at low strains and shows a more uniform increase of stiffness at high strains. Forming curves in the case of straight ribs are shown in Fig.17: two curves are reported for each condition in order to underline the good repeatability. In analogy with SBR dies, sheet forming occurs at lower displacements by using shaped dies but an opposite trend is observed as regards the rib width: higher forces are necessary to stamp narrower ribs.

Some forming tests were also performed by using lower dies made of PA rather than aluminium: results are reported in Fig.18. The forming curves are superimposed so as to indicate that a negligible difference is present, and also formed parts did not differed significantly: even if the PA die is much

softer than the aluminium die, its stiffness is greatly higher than the SBR die stiffness. Therefore the difference in the die stiffness between aluminium and PA die cannot be appreciated by using SBR upper dies. Despite of the tribological properties of PA, significant differences in friction forces were not observed too, as the forming curves should have been affected by that.
Even if the die durability increased greatly by using SBR dies in comparison with SR dies, in any case a complete forming was not obtained: tearing occurred first at high displacements (Fig.19). However, the ability of matching the lower die with the aluminium sheet was improved.

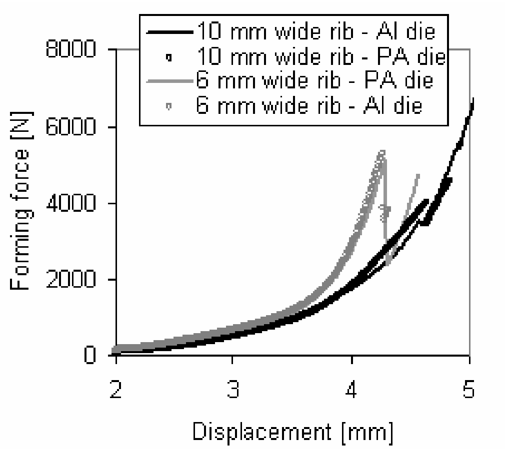

Fig. 18. Forming curves for straight ribs with shaped SBR upper dies and lower aluminium (Al) and PA dies

Fig. 19. Straight ribs formed by SBR shaped dies

3.3 PA dies

Forming tests were performed by using a PA upper die in combination with a PA lower die or an aluminium lower die. The comparison between the two different stamping conditions is reported in Fig.20 for the case of straight ribs. Also in this graph two curves are shown for each experimental condition, and good test repeatability is quite evident.
For the first time, a relative maximum is visible with a subsequent plateau. After the plateau, the forming curves rapidly increases in slope due to the die contact. Some oscillations are visible in the case of the aluminium die after the maximum, probably because of the friction between the formed sheet and the die. By decreasing the rib width, lower initial slopes of the forming curves are obtained and, generally, higher plateau values. However, the strongest effect is related to the reduction of the forming forces in the case of both dies made of PA, even if the part formability seems to be very similar.
PA dies showed a high durability combined with the ability of completely forming aluminium sheets (Fig.21): no tearing was observed. In order to measure the part spring-back after stamping, the external profile of the straight ribs was acquired by means of a 3D profilometer. In Fig.22 a typical profile is shown.

4. NUMERICAL SIMULATION

Numerical analyses were carried out to deepen the forming mechanism of the straight ribs. In order to reduce the computational time, the model was simplified: a 2D model was built in Deform 2D, the dies were considered rigid elements and a generic 1200 aluminium alloy was set for the simulation. A low friction coefficient was applied between the PA die and the sheet (about 0.2) and a high friction coefficient (1.0) between the aluminium die and the aluminium sheet. Fig.23 shows the appearance of the numerical model at the initial condition and during forming; in Fig.24 the simulation of the wider rib forming is reported in terms of forming curves for two different conditions: upper and lower die made of PA; upper die made of PA and lower die made of aluminium.
Apart from scattering of numerical results, due to the large mesh size, a sufficient agreement was found between numerical and experimental data. In particular, numerical data confirm that lower forming forces are necessary in the case of PA dies and the entity of these forces mainly depends on the friction.

5. DISCUSSION

A comparison between the different die materials is shown in Fig.25 in the case of straight ribs, 10 mm wide. Only by means of PA dies a complete forming was obtained without sheet tearing: this occurrence is related to the appearance of a relative maximum in the forming curves. However it is evident the strong effect of the die material on the forming mechanism.
As reported, best results were obtained by using both dies made of PA: in this case the combination of low friction and optimal stiffness lead to a complete matching of the aluminium sheet with the dies. The stiffness is high enough to preserve the shape during forming, but also soft enough to deform under forming forces. Thanks to the die deformation, localized pressures at the sheet-die interface lead to the reduction of the sheet spring-back. This effect was measured by calculating the slope of the undeformed portions of the rib (Fig.22). In Fig.26 the spring-back is reported in terms of angular deviation of these plane portions from the initial plane sheet (Fig.27). The lowest angular deviations were obtained by using a combination of dies (PA and aluminium) for both straight ribs. Instead a trend was not found in dependence of the rib width.

6. CONCLUSIONS

Soft materials can be used for flexible forming but it is hard to set the process due to their low durability.

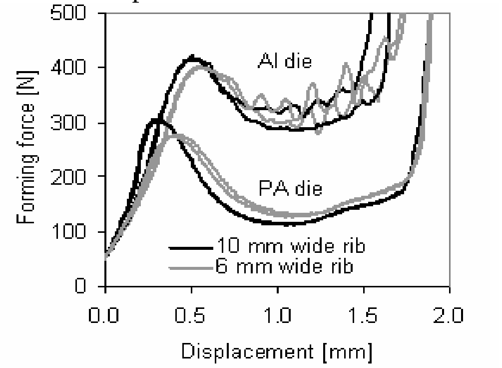

Fig. 20. Forming curves for straight ribs with shaped PA upper dies and different lower dies

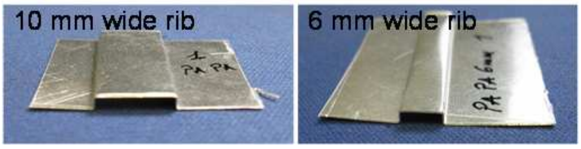

Fig. 21. Straight ribs formed by PA dies

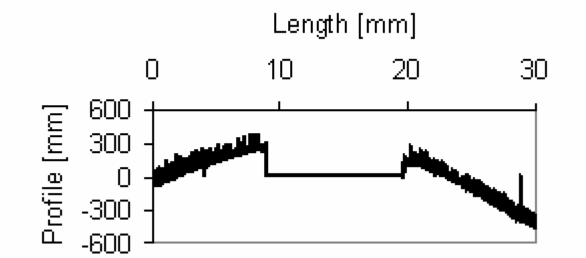

Fig. 22. Typical profile of a 10 mm wide rib formed with PA die

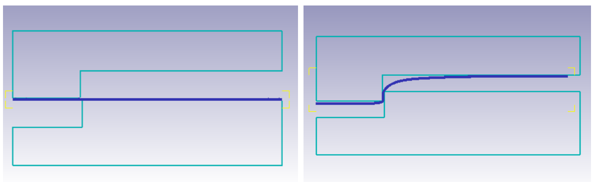

Fig. 23. Numerical analysis of straight rib forming: initial stage (left) and during forming (right)

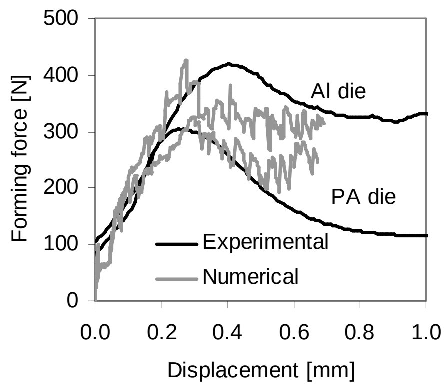

Fig. 24. Comparison between experimental data and numerical solutions for straight ribs

Moreover, a suitable process design is necessary to avoid sheet wrinkling or tearing. Semi-rigid plastics showed better results in terms of reduced forming forces, die durability and spring-back. However, also in this case, the best solution seems to be the combination of a semi-rigid die with a rigid one.

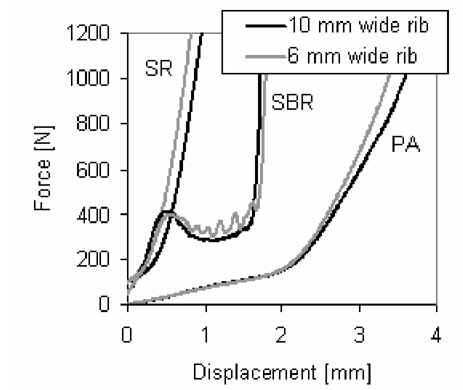

Fig. 25. A comparison between forming curves obtained with different die materials in the case of the 10 mm wide rib

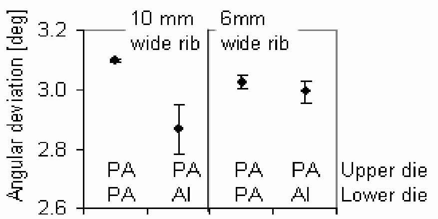

Fig. 26. Angular deviation of formed straight ribs by PA dies

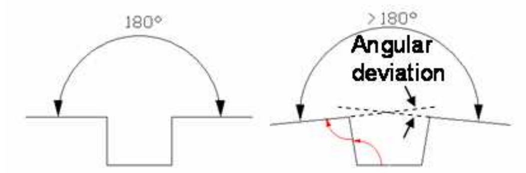

Fig. 27. Evaluation of part spring-back

7. ACKNOWLEDGEMENTS

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